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THERMAL AND HYDRAULIC BEHAVIOR OF CANDU CORES UNDER SEVERE ACCIDENT CONDITIONS - EXECUTIVE SUMMARY

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ABSTRACT

This report summarizes the results of a study of the thermo-hydraulic behavior of CANDU cores under accident conditions more severe than those normally considered in the licensing process. A comprehensive description and complete results of the study are given in the main report.

RÉSUMÉ

Le présent rapport résume les résultats d'une étude sur le comportement thermo-hydraulique du coeur des réacteurs CANDU dans des conditions d'accident plus sérieuses que celles que l'on considère normalement au cours du processus d'autorisation. Le rapport principal fournit la description détaillée de l'étude et de tous ses résultats.

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A. INTRODUCTION

In a CANDU nuclear power reactor, the short (0.5m long) fuel bundles, 12 per channel, are supported in horizontal Zircaloy pressure tubes about 6m long through which the heavy-water coolant flows. The number of pressure tubes depends on the thermal power of the reactor; there are 480 in a Bruce-A reactor unit (~2700 MW(th)). Surrounding each pressure tube is a concentric calandria tube. A trickle flow of gas (CO_2 or N_2) occurs along the channel in the annulus between the two tubes. Outside the calandria tubes is the cool heavy-water moderator contained in the calandria itself. The purpose of the gas-filled annulus is to keep heat losses from the coolant to the moderator at acceptably low levels during normal operation. The moderator is maintained at a low temperature (~ 80°C) by a separate cooling circuit. The cool moderator surrounding the calandria tubes provides a potential heat sink following a LOCA should the emergency coolant injection (ECI) fail or be impaired. Studies have shown that fuel will not melt in such an accident because of heat transfer to the moderator [1,2,3,4].

Figure 1 is an isometric view of a typical CANDU reactor core. It should be noted that the calandria vessel is surrounded by separately-cooled ordinary water in the shield tank which is contained within the calandria vault wall which forms the main concrete shield.

A study has been undertaken for the Atomic Energy Control Board to assess the behavior of CANDU reactor cores, in particular, a Bruce-A reactor core (~ 2700 MW th), under accident conditions more severe than those considered in normal licensing processes. The study was not intended to be a comprehensive risk investigation; only a limited number of severe accidents was examined, mainly thermo-hydraulic physical processes were analyzed and no calculations of event-sequence probabilities were made. The complete results of the study are given in reference [5]. Certain aspects of the study are described in references [6] to [8].

An event tree, as shown in Figure 2, was developed to identify potential accident sequences following a large LOCA. The code letters used to identify events in Figure 2 are defined under Nomenclature. In this study accident sequences S11 to S14 were analyzed:

S11: LOCA + LOECI + LOMCS
S12: LOCA + LOECI + LOMCS + CI
S13: LOCA + LOECI + LOMHS
S14: LOCA + LOECI + LOMHS + CI

Event sequences and core behavior are identical for sequences S11 and S12, although radioactive releases from containment would be different. The situation is the same for sequences S13 and S14.

B. DESCRIPTIONS OF ACCIDENT SEQUENCES

In accident sequences S11 and S12, a late-stagnation LOCA with failure of emergency cooling injection results in the pressure tubes overheating and sagging onto the calandria tubes, providing an effective heat flow path to the moderator [1]. The moderator cooling system fails, the moderator heats up and the calandria pressure increases until the rupture disks on the calandria relief ducts break, at about 140kPa(g). See Figure 1. The calandria pressure drops to that of the reactor vault. Some moderator is lost through the ducts by liquid swell and sub-cooled void generation. The moderator begins to boil. As boiling develops, liquid moderator is rapidly expelled through the relief ducts by void formation and additional moderator

is lost by vaporization. As the void fraction near the top of the calandria increases, the top row of calandria tubes becomes uncovered, causing a rapid temperature rise of these tubes, now cooled by convection and radiation to steam generated by the boiling moderator. Pressure tube and fuel-temperatures also increase. The exothermic reaction between the Zircaloy calandria tubes and the steam causes further increases of fuel channel temperatures. Eventually, other rows of tubes are also uncovered and similar subsequent behavior occurs.

Uncovered fuel channels eventually disintegrate by melting or other mechanisms and fall to the bottom of the calandria, probably causing disintegration of any lower uncovered fuel channels as they fall (Cascading failure). The hot debris from these channels is quenched by moderator remaining in the calandria. Mixing of molten debris with moderator may result in vapor explosions. Fission products escape from the calandria to the reactor vault. Deuterium gas from the Zircaloy-heavy water reaction also escapes to the reactor vault. The steam and deuterium discharges, and possible deuterium combustion, cause pressure increases in containment, which may result in containment failure.

Eventually, all the moderator is expelled from the calandria and the quenched debris is uncovered and heats up again. The debris melts and forms a molten pool, supported by the calandria wall, which is cooled by the shield tank water. The molten pool may boil. The calandria wall may melt or fail and the molten material mix with the shield-tank water which may result in a vapor explosion and which, once again, would quench the debris. The shield tank water may be expelled and/or boil off into containment and the core debris may heat up and melt once more. Molten material may melt through to the fuelling machine duct and through the floor of the duct into the underlying rock. Interaction of the molten pool with concrete would generate non-condensible gases which may cause containment failure, if it has not already occurred. Eventually, molten material would solidify in the concrete or the underlying rock.

In accident sequences S13 and S14, it is assumed that a rupture of a moderator outlet pipe occurs simultaneously with the LOCA and LOECI. Subsequent events will be similar to those in S11 and S12 except that moderator will be lost from the calandria more rapidly and fuel channels will disintegrate earlier.

C. ANALYTICAL APPROACH

It is recognized that the behavior of core components under the extreme conditions of this accident sequence is, in general, quite speculative since little experimental information on CANDU core component behavior and physical phenomena under these conditions is available. The approach used has been to attempt to model the essential features of the behavior of core components and the moderator on a physically-sound basis, as far as possible, and to undertake sensitivity studies of the effects of the important parameters at the different stages of the accident sequence. In some cases, bounding analyses have been used.

Six computer programs were developed to permit these accident sequences to be analyzed, as follows:

- **IMPECC-UCZ:** analysis of thermal behavior of uncovered calandria tubes
- **MODBOIL:** analysis of moderator boiling and expulsion, allowing for disintegration and quenching of uncovered fuel channels
- **DEBRIS:** analysis of thermal behavior of a porous bed of dried-out

solid core debris

MOLTENPOOL: analysis of thermal behavior of a molten pool of core debris, for non-boiling or boiling conditions

CONFILM: analysis of condensation of vaporized core debris on a calandria wall

BLDG: analysis of pressurization of containment

These computer programs are described in detail in reference [5].

The sequences of events in these accident sequences have been analyzed by developing a detailed analytical flow chart which identifies the various stages of the accident sequence, the analytical steps required for their assessment and relates the stages and analytical steps to each other. The analytical flow chart is given in reference [5], and an example portion of this chart is given in reference [6]. This chart was used as a guide in developing the analytical models and computer programs used in the study.

D. METHODS AND RESULTS

The methods used and results obtained in accident sequences S11 and S12 are presented first, followed by those for sequences S13 and S14.

1. Heat Source to Moderator

For the large LOCA considered here, the primary system blowdown lasts about 170 seconds [2,5]. After this time, decay heat, stored heat and heat generated by the Zircaloy-steam reaction within the fuel channels are transferred from the fuel channels to the moderator. The total heat source to the moderator was determined by grouping fuel channels according to average powers into four groups and applying the IMPECC program [2,3,4,5,9], which uses the ANS decay heat source, to each group to establish the heat flow rate to the moderator, for the case of pressure tubes sagging onto calandria tubes, at a pressure tube temperature of 1000°C [1]. Allowance was made for heat generated within the channels by the exothermic Zircaloy-steam reaction, using information from the Whiteshell Nuclear Research Establishment of AECL [10]. The result is shown in Figure 3. The peaks in the curve during the period that the heat source is increasing represent the rapid discharges of stored energy from the pressure tubes as those in each group sag onto the calandria tubes [11]. The heat source shown in Figure 3 applies as long as all the calandria tubes are submerged in the moderator.

2. Expulsion of Moderator and Behavior of Uncovered Fuel Channels

An explicit, finite-difference computer program, MODBOIL [5,6,7], has been developed to analyze the thermo-hydraulic behavior of the moderator in this accident sequence.

In MODBOIL, the moderator is divided into 24 horizontal slices, one for each row of fuel channels, which are the control volumes in the analysis. The time-dependent heat source for each slice is pro-rated from the overall heat source in Figure 3, accounting for the number of fuel channels in each slice and their average power ratings. Transient heat and mass balances are made on each slice for non-boiling, sub-cooled boiling and bulk boiling conditions. Under non-boiling conditions, two options are available, perfect mixing or no mixing of liquid among slices. No significant differences in overall moderator behavior were found for these two extreme cases.

MODBOIL calculates the moderator swell, the pressure over the moderator,

the time to failure of the calandria rupture disks, the initiation and development of sub-cooled and bulk boiling of the moderator, the void fractions in each slice, the pressure distribution throughout the calandria allowing for static head effects, two-phase flow-pressure losses and choked flow in the relief ducts and the rate of moderator expulsion from the calandria. It also determines the times of effective uncovery of fuel channel rows and allows for heat source re-distribution from any moderator slice to the bottom slice to model the disintegration of uncovered fuel channels. Criteria for fuel channel disintegration were established using IMPECC-UCZ [5,6,7] which models the thermal behavior of uncovered fuel channels allowing for radiative and convective heat transfer to steam flowing over the calandria tubes and for heat generated by the reaction between this steam and the Zircaloy calandria tubes. For representative channel uncovery times, steam flow rates and temperatures, IMPECC-UCZ shows that the fuel in uncovered channels will still be well below the UO_2 melting temperature up to the times of channel disintegration [5,6,7], as can be seen in Figure 4. Some melting of calandria tube Zircaloy may occur in this period, as indicated, for example, in Figure 5, but the amounts will be limited since most Zircaloy will have been oxidized before its melting temperature is reached and predicted temperatures do not reach the melting point of ZrO_2.

The MODBOIL program models the quenching of disintegrated fuel channel debris in the bottom slice of moderator, allowing for stored and decay heat and assuming film boiling (plus radiation) or nucleate boiling as appropriate.

2.1 Moderator Behavior Before Channel Uncovery

Results show that rupture disk failure occurs at about 9.2 minutes and that liquid begins to spill from the relief ducts at about 9.4 minutes. Bulk boiling begins in the top slice just before 16 minutes and propagates downwards rapidly until it becomes fully developed across the calandria at about 17.6 minutes. The rapid increase in void fraction in this period results in a large fraction of moderator being rapidly expelled from the calandria, as can be seen in Figure 6. Moderator is expelled in surges during this period, as shown in Figure 7, but the accompanying pressure surges are not severe, as shown in Figure 8, because of the low steam qualities at the exit of the relief ducts ($\lesssim$4%) during this period.

2.2 Moderator Behavior After Channel Uncovery

After channel uncovery begins, reference conditions used to define the behavior of the core are:

(a) Delay times between channel uncovery and disintegration established from IMPECC-UCZ runs, as described in references [5] and [7].

(b) Fraction of channel mass disintegrating = 1.0 (FRCMAS = 1.0).

(c) Fraction of Zircaloy molten at disintegration = 1.0 (FRMELT = 1.0).

(d) Average temperature of fuel at disintegration = 1750°C (TF)

(e) Average temperature of Zircaloy (solid or molten) at disintegration = 1750°C (TZIRC)

(f) Uncovered channels disintegrate when struck by falling debris (Cascading failure)

It is judged that these are the most severe conditions for core and moderator behavior that might occur in this accident sequence. The rationale for the choice of these reference conditions is discussed in reference [5].

For these conditions, MODBOIL predicts that the top row of channels becomes uncovered at about 21 minutes and that the initial disintegration of fuel channels occurs at about 23 minutes, when the top three rows collapse simultaneously. This and subsequent channel disintegrations cause the later flow rate and pressure surges shown in Figures 7 and 8, respectively. Essentially all the moderator is expelled from the calandria in about 48 minutes, as shown in Figure 6.

As the reference condition temperatures, as established from IMPECC-UCZ [5,7], indicate, the fuel material will not be molten at the times of disintegration and MODBOIL shows that it will be rapidly quenched as it falls into the moderator. Although the reference conditions assume that all channel Zircaloy is molten at disintegration, only a fraction of the calandria tube Zircaloy is likely to be molten at this time since the fuel sheaths and pressure tubes will have already been oxidized and a significant fraction of the calandria tube Zircaloy will also have been oxidized, as discussed earlier. The melting point of ZrO_2 (~2700°C) is well above the anticipated peak temperatures of the non-fuel materials in the channels. See Figure 5. Thus, almost all of the non-fuel debris also will fall into the moderator as solid material. MODBOIL shows that, whether molten or not, all non-fuel debris will also be rapidly quenched in the moderator. Finally, for the reference conditions, average debris temperatures will be about 110°C just before the last of the moderator is expelled from the calandria at about 48 minutes and only a few fuel channels (at an average temperature of ~1750°C) will remain intact at that time.

Results of sensitivity studies, as given in references [5] and [7], show that the average moderator expulsion rate and time to complete expulsion are not likely to be much different from those for the reference conditions, even for the case in which no delay is assumed to occur between calandria tube uncovery and channel disintegration ("instantaneous disintegration"). The study has also shown that steam superheated by, and deuterium gas generated from, the uncovered calandria tubes will not have any significant effects on calandria pressure nor on discharge rates from the calandria [5].

The investigation also concluded that no vapor explosion would occur as the core debris falls into the remaining moderator [5].

3. Thermal Behavior of Bed of Core Debris

Following moderator expulsion, a bed of solid core debris is left at the bottom of the calandria. It is not possible to predict the physical and geometric characteristics of this debris bed with any confidence, so that a simple one-dimensional thermal model which would facilitate sensitivity studies was developed.

In the model, it is assumed that the debris forms a uniform porous bed of UO_2 and ZrO_2 material with porosity and average pore size to be specified as inputs to the computer program DEBRIS. Mechanisms of heat transfer considered are conduction through solid material, allowing for random contact thermal resistances, and conduction and radiation through the steam-filled pores. Considering these mechanisms, an equivalent effective thermal conductivity of the bed was determined. The volumetric heat source used is

based on the ANS decay heat source, with the dilution effects of structural material and bed porosity accounted for.

The upper surface of the debris bed is assumed to be cooled by natural convection to steam and radiation to the calandria walls above the bed, which are cooled by the shield-tank water. The lower surface of the bed, resting on the calandria wall, is cooled by conduction through the wall and natural convection or sub-cooled boiling to the shield-tank water, with the program selecting the appropriate mechanism, depending on the existing conditions at any time.

Figure 9 shows maximum, upper and lower surface temperatures of the debris bed as functions of time for the selected reference conditions. The maximum temperature in the bed reaches the melting point, ~2700°C, at about 85 minutes after the start of re-heating, or about 135 minutes after the initiation of the accident. The upper and lower surface temperatures of the bed are well below the melting point at this time. The lower surface temperature is well below the melting temperature of the stainless steel calandria wall and the lower surface heat flux into the shield tank water, 15.5 W/cm^2, is well below the critical heat flux, estimated at about 280 W/cm^2 for these conditions [5]. Thus, the calandria wall will remain well-cooled and will retain its integrity up to at least the time at which bed melting begins.

The reference conditions used for porosity and average pore size, 0.5 and 0.03m respectively, are arbitrary, although the large pore size selected reflects a judgement as to the nature of the debris, considering that little or no melting will have occurred before bed uncovery. However, sensitivity studies show that predicted results are very insensitive to wide variations, separately and jointly, in these parameters as well as to significant variations in solid material thermal conductivity and the contact conductance parameter [5]. For example, Figure 9 shows that the predicted temperatures for bed porosities of 0.1 and 0.8 are only slightly different from those for the reference condition porosity of 0.5.

4. Thermal Behavior of a Molten Pool of Core Debris

Once melting begins in the debris bed, some time will be required for the transition to a completely molten pool. Because of the complexity of this transition stage [5], no attempt was made to develop an analytical model for the debris during this period. Instead, the time required for this period and the accompanying heat source decay were ignored, giving a conservative analysis. Thus, for the reference conditions, the earliest time for complete molten pool conditions was taken as 135 minutes.

A quasi steady-state, modified one-dimensional energy balance is the basis of the model in the program MOLTENPOOL for the thermal behavior of the pool, in which allowance is made for the curvature of the calandria wall forming the lower surface of the pool.

Internal radiation heat transfer, which is important in high-temperature molten pools [12], is accounted for using the method of Anderson [13].

For non-boiling conditions, the correlation of Kulacki and Goldstein [14] was used to predict internal heat transfer coefficients for the top surface, and the results of Mayinger, et al., [15] and of Gabor, et al. [16] were combined to predict the internal heat transfer coefficient for the bottom surface.

For boiling conditions, the upward heat flux, and the pool-average void fraction, were established from the vapor volumetric flux density determined from the work of Ginsberg, et al. [17], while the downward heat transfer coefficient was taken from the work of Gabor, et al. [16].

A major uncertainty in this analysis is that of liquid and vapor property values for the molten pool materials. Data used for the liquid are mainly those of Anderson [13], while those for the vapor were estimated or taken from various sources [5]. Four different sets of consistent property values were used to determine the sensitivity of results to uncertainties in property values.

Results for the reference conditions obtained using the program MOLTENPOOL, were inconclusive as to whether the pool would boil or not, with two sets of property values predicting no boiling and two sets predicting boiling. Nevertheless, the maximum predicted downward heat flux, i.e., the heat flux through the calandria wall into the shield tank water, did not exceed 20 W/cm^2 for any of the four sets of property values.

Heat fluxes of 20 W/cm^2 are still well below the estimated critical heat flux of 280 W/cm^2 for the conditions in the shield tank water [5], so that the calandria wall will be well-cooled throughout this stage of the accident sequence, irrespective of the uncertainties in molten pool liquid or vapor property values and whether the pool boils or not.

5. Interaction of the Molten Pool with the Calandria Wall

Although the calandria wall should remain well-cooled during this stage of the accident sequence, provided that the shield-tank water cooling system is operational, the possibility of partial calandria wall melting and failure exists.

To investigate this question, the asymptotic behavior of the molten pool on the calandria wall under quasi-steady state conditions was analyzed using a one-dimensional model. From this analysis, the conditions for wall melting were established, as shown in the non-dimensional plot in Figure 10, where $\emptyset$ represents a non-dimensional source heat flux from the molten pool and Bi_{ac}, the coolant Biot number, represents the cooling capability of the shield tank water.

For the highest predicted heat flux from the non-boiling molten pool for the reference conditions, the shield tank water will be undergoing sub-cooled nucleate boiling on the calandria wall [5]. For these conditions, $\emptyset = 0.285$ and $Bi_{ac} = 5.10$, so that Figure 10 shows that there will be no melting of the calandria wall, and that, furthermore, these conditions ensure that the wall is very far from the melting point. The analysis also showed that a solidified crust of core material about 2.3 cm thick would form on the wall, thus providing a protective shield. Further analysis showed that the heat flux from the pool would have to be about 100 W/cm^2, about five times the maximum predicted value for the reference conditions, before any melting of the calandria wall would begin [5].

For the property values which predict that the molten pool will boil, the heat flux into the calandria wall is less than the maximum for non-boiling conditions, so that the calandria wall under the surface of the pool will be also well protected and cooled and far from the initiation of melting in this case [5]. However, the vaporized core debris will condense on the

calandria wall above the pool surface, and the resulting high heat fluxes may cause melting of the calandria wall. A simple model of this process was developed and embodied in the computer program CONFILM. The model assumes that a quasi-equilibrium state would be established between evaporation of core material from the surface of the pool and its condensation on the calandria walls above the pool. The condensation heat transfer coefficient was established assuming that conventional correlations apply and that the condensing film was under laminar flow conditions. Results show that the average condensation heat flux for the reference conditions in this case is considerably higher than that from the molten pool itself, about 50 to 55 W/cm^2, depending on the property values used. However, these values are still well below the critical heat flux for these conditions so that the calandria wall above the pool surface will remain well cooled. Also, the interaction of the condensate film with the calandria wall was assessed using the quasi-steady state model discussed earlier. This assessment showed that this portion of the wall would also be far from any initiation of melting and would be protected by a solidified layer of debris about 1.0 cm thick [5].

6. End Point for Accident Sequences S11 and S12

The analysis of these accident sequences shows that the core material debris, whether solidified or molten, will not jeopardize the integrity of the calandria vessel, irrespective of whether the molten pool boils or not. Calculations with MOLTENPOOL show that, eventually, the molten pool would begin to resolidify at a time between 10 and 50 hours, depending on the molten material property values. Thus, we can conclude with good confidence that essentially the entire mass of core material will be contained within the calandria, as long as the shield-tank cooling water system functions properly. The calandria, in effect, acts as an effective inherent core catcher in a CANDU reactor.

Therefore, we also conclude that the subsequent stages of the accident sequence, as listed earlier in this paper, would not be experienced should this accident actually occur.

7. Containment Pressurization and Effects

Since the vapor discharge rates into containment from the calandria, even during the surges resulting from multi-channel disintegration, are much lower than those experienced during primary system blowdown in a large LOCA, a simple single-node model of containment was used in the program BLDG. The model allows for deuterium gas as well as moderator liquid and vapor expulsion from the calandria with expulsion rates being taken from results of appropriate MODBOIL runs. The effects of the reactor vault coolers and of condensation on the containment walls allowing for the significant effects of non-condensibles, are accounted for in the model. It is assumed that all the dousing water in the vacuum building has been used in coping with the initial LOCA, so that none is available to temper the additional effects of this accident sequence.

For initial conditions taken from those expected following a large LOCA in a Bruce unit, and assuming that the entire containment volume, including the vacuum building, is available, the predicted containment pressure and temperature histories for the reference conditions are shown in Figure 11. Figure 11 shows that a peak pressure of about 165 kPa absolute is reached at about 50 minutes into the accident. The maximum pressure difference across the containment boundary is thus about 64 kPa, slightly higher than

the design pressure difference of a 50 kPa but below the test pressure difference of 80 kPa. The results for "instantaneous" disintegration conditions in Figure 11 show an even lower peak pressure, ~135 kPa absolute. Sensitivity studies show that, should the vacuum building volume not be available after the initial LOCA because of failure of all the containment pressure relief valves to re-open, the absolute peak containment pressure would still be only about 215 kPa [5].

The additional maximum concentration of deuterium gas in containment resulting from this accident sequence is predicted to be about 8.6%, so that there may be some increased probability of deuterium gas combustion [5].

Thus, we can conclude that this accident sequence would not cause serious damage to nor failure of containment, even when the vacuum building is not available [18].

Gap-inventory fission products would begin to escape to containment early in the accident sequence, but the actual build-up of radioactivity in containment would probably be delayed because of the solubility of iodine in the remaining moderator [19]. Major releases of the bound fission products would not begin until fuel melting begins some 135 minutes after the initial LOCA. At this time, the containment absolute pressure is predicted to be about 132 kPa, for the reference conditions, or 123 kPa, for "instantaneous" disintegration conditions, and it will continue to fall thereafter. Therefore, there will not be a significant pressure difference across the containment boundary during the period when the major release of bound fission products occurs, so that radio-activity releases from containment would be relatively low.

8. Accident Sequences S13 and S14

In accident sequences S13 and S14, moderator expulsion from the calandria will be more rapid than in S11 and S12 because of the draining of the moderator through the 12 inch (0.305 m) moderator inlet pipe. Because of this rapid discharge from the calandria, the heat source to the moderator was ignored in this case since little heat will have been transferred to the moderator by the end of the discharge period.

Consistent with the assumption of no heat flow from the fuels channels to the moderator during moderator discharge, fuel temperatures were calculated on an adiabatic basis after EOB is reached. As in the previous sequences, channel failure is assumed to occur when the maximum fuel temperature in a row reaches 1750°C [5], and all uncovered rows are assumed to disintegrate if struck by a higher disintegrating row.

Rather than modify MODBOIL to predict moderator expulsion rates under these conditions, simple bounding analyses were used to predict upper and lower limits of the time for complete moderator expulsion from the calandria, depending on whether the relief duct rupture disks break or not [5]. Before any channel disintegration occurs, the analyses consider moderator drainage under moderator static head with a vapor-space pressure equal to the moderator saturation pressure.

For the reference conditions, the model predicts that initial channel disintegration would occur at about 410 seconds, when the top nine rows would disintegrate simultaneously.

Without modifying MODBOIL, it is impossible to establish whether the pressure surge accompanying this initial disintegration would break the rupture disks or not. However, the predicted moderator behavior for the two bounding cases is shown in Figure 12, from which it can be seen that the total discharge time in these accident sequences will be between 11 and 17 minutes. To be conservative, a total discharge time of 10 minutes was chosen as the reference value.

Some of the fuel channel debris will have been quenched by the moderator before it has been finally discharged, but some will not have been quenched because of the rapid discharge of the moderator. Therefore, to be conservative, it was assumed that all debris at the bottom of the calandria is at 1750°C, the assumed disintegration temperature, when the debris bed is initially dried out. Other reference conditions for the debris bed were assumed to be the same as those for the previous accident sequences. The program DEBRIS was then used to establish the time at which gross melting would begin in the debris. For the reference conditions, DEBRIS predicts that the total time to the initiation of gross fuel melting will be about 30 minutes. The analysis also showed that the calandria wall would remain well-cooled and intact.

As in the previous accident sequences, the transition period from the initiation of melting to complete melting of the core debris was ignored, and the behavior of a molten pool of core debris was assessed at a time of 30 minutes, using MOLTENPOOL. Again results were inconclusive as to whether the molten pool would boil or not, with two sets of property values indicating that it would and the other two sets that it would not. Nevertheless, as before, the maximum heat fluxes into the shield tank (~30 W/cm^2) are still well below the critical heat flux. Also, for the most severe conditions, values of $\beta = 0.427$ and $Bi_{ac} = 7.51$ were estimated, so that Figure 10 shows that, again, there would be no melting of the calandria wall, and that conditions are very far from those required for melting. The analysis also predicts that a solid crust thickness of about 1.5 cm would protect the calandria wall.

For the property values which predict that the molten pool might boil, CONFILM was used to assess the effect of a condensing film of core-debris vapor on the calandria wall above the boiling pool. In this case, the condensing heat transfer coefficient was increased above the calculated laminar value, allowing for turbulence and/or drop-wise condensation, on the assumption that all core vapor would condense on the calandria walls, i.e., that none would escape from the calandria. Under the higher condensing fluxes in this case, a very small molten layer might form on the inner surface of the calandria wall, about 2 mm thick, but the bulk of the wall would be well below the melting point and would remain well cooled.

Considering the conservative analysis, it is concluded that the calandria wall would be well-cooled and would maintain its integrity in these accident sequences.

Again, we conclude that the core debris would be contained within the calandria, provided that the shield tank cooling system continues to function. That is, the calandria, once again is an effective core catcher [5].

Containment pressurization would be less in these accident sequences than in S11 and S12, so that its integrity would not be threatened and there would not be significant releases of fission products from containment.

E. CONCLUSIONS

Important conclusions reached in the study of these accident sequences are summarized below, first for accident sequences S11 and S12, and then for S13 and S14.

1. Conclusions for Accident Sequences S11 and S12

(1) The operators would have about 20 minutes to provide an alternate heat sink for the moderator before channel uncovery and disintegration begin.

(2) The moderator would be completely expelled from the calandria in about 45 to 50 minutes.

(3) No gross fuel melting would occur even when fuel channels are uncovered, and fuel in the core debris in the bottom of the calandria would not begin to melt until about 135 minutes after the accident begins.

(4) The calandria walls would not melt nor suffer significant damage from molten core debris, even though boiling of the molten pool may occur, provided that the shield-tank water cooling system remains operational.

(5) Core debris would be contained within the calandria and would begin to re-solidify in the period of 10 to 50 hours after the initiation of the accident. The calandria serves as an inherent core catcher in a CANDU reactor.

(6) Pressurization of containment during the accident sequence would not cause containment failure nor result in excessive releases of fission products outside containment.

2. Conclusions for Accident Sequences S13 and S14

Although the moderator will be expelled much more rapidly from the calandria in these cases than in S11 and S12, and although gross fuel melting will begin at about 30 minutes instead of 135 minutes, once again the calandria will act as an effective core catcher. Also, pressurization of containment and fission products would be less severe in these accident sequences.

3. General Conclusions

Of course, there are considerable uncertainties in the properties and behavior of CANDU core materials under the extreme conditions encountered in this accident sequence, so that the results must be treated with caution until such time as work on these topics [e.g., 20, 21] yields further information.

The present study applies for a late-stagnation LOCA, in which pressure tubes sag onto calandria tubes. A similar study has not been done for an early-stagnation LOCA in which pressure tubes balloon into contact with calandria tubes [1]. However, it is judged that similar results would be obtained and that the core debris would again be contained within the calandria for this latter case.

While no assessment of event probabilities was made as part of this study, rough estimates of the probability of this accident sequence indicate a value considerably less than 10^{-7} per reactor year. With such a low probability, the recommendations of reference [22] would not require that this accident sequence be considered in a licensing application.

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[11] Only three peaks are shown instead of the expected four since the first peak, being small, was obscured in the computer plot. Of course, should such an accident actually occur, the power increase would be much smoother, since pressure tubes would not actually sag in four groups, but more or less individually.

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G. ACKNOWLEDGEMENTS

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H. NOMENCLATURE

Bi_{ac} - $\frac{h_c \delta_a}{k_w}$, Biot number for shield tank water on calandria wall

CI - Containment impairment

CON - Containment

DF - Dual Failure

ECI - Emergency coolant injection

ECLT - Emergency cooling - long term

FEPR - Fuel element power rating, W/cm

FRCMAS - Fraction of mass of uncovered, disintegrated channels which falls to bottom of calandria

FRMELT - Fraction of Zircaloy in mass of fallen channels which is molten

h_c - Heat transfer coefficient for shield tank water on calandria wall, W/m^2k

k_w - Thermal conductivity of calandria wall, W/mK

LOCA - Loss-of-coolant accident

LOECI - Loss of emergency core-cooling injection

MCS - Moderator cooling system

MHS - Moderator heat sink

q_b - Heat flux from molten pool into calandria wall, W/m^2

SD - Shut down (special safety system)

SF - Single failure

T_c - Temperature of shield tank water, ^oC.

T_m - Melting temperature of calandria wall, ^oC.

TCT - Calandria tube temperature

TF, TF1 - Fuel temperature

TRS - Steam temperature

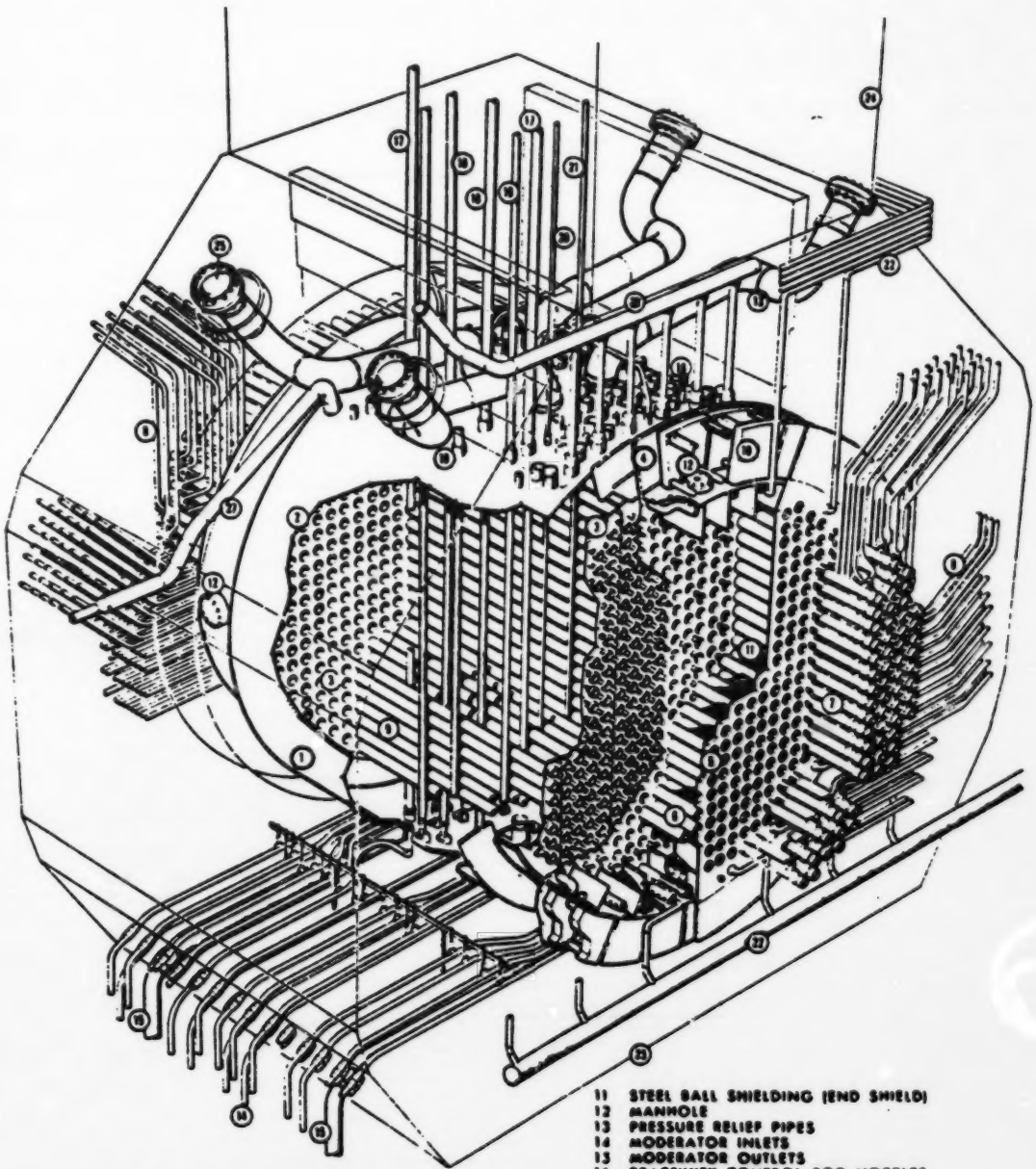
TZIRC - Temperature of Zircaloy, ^oC

δ_a - Calandria wall thickness, m

δ_s - Solidified core-debris crust thickness, m

ε_v - propsity of debris bed

ϕ - $\frac{q_b \delta_a}{k_w(T_m - T_c)}$, non-dimensional heat flux into calandria wall from molten pool of core debris.



1 CALANDRIA
2 CALANDRIA SHELL
3 CALANDRIA SIDE TUBE SHEET
4 BAFFLE PLATE
5 FUELLING MACHINE SIDE TUBE SHEET
6 LATTICE TUBE
7 END FITTINGS
8 FEEDERS
9 CALANDRIA TUBES
10 SHIELD TANK SOLID SHIELDING
11 STEEL BALL SHIELDING (END SHIELD)
12 MANHOLE
13 PRESSURE RELIEF PIPES
14 MODERATOR INLETS
15 MODERATOR OUTLETS
16 REACTIVITY CONTROL ROD NOZZLES
17 BOOSTER ROD
18 SHUT-OFF ROD
19 ZONE CONTROL ROD
20 FLUX MONITOR
21 FLUX MONITOR AND POISON INJECTION
22 END SHIELD COOLING PIPING
23 SHIELD TANK
24 SHIELD TANK EXTENSION
25 RUPTURE DISC ASSEMBLY
26 MODERATOR INLET HEADER
27 MODERATOR OVERFLOW

FIG. 1 CANDU REACTOR ISOMETRIC DIAGRAM

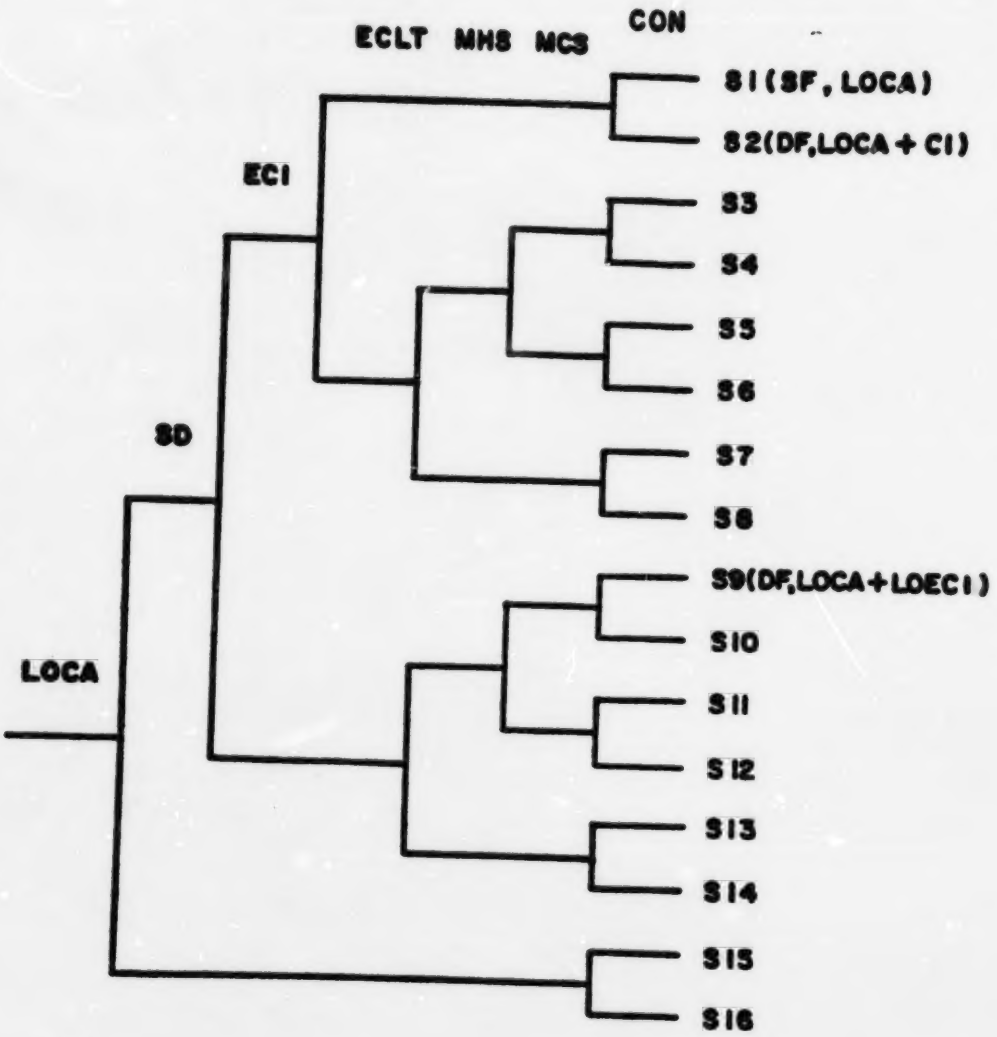


FIG. 2 CANDU LOCA FUNCTIONAL EVENT TREE, ACCIDENT SEQUENCES

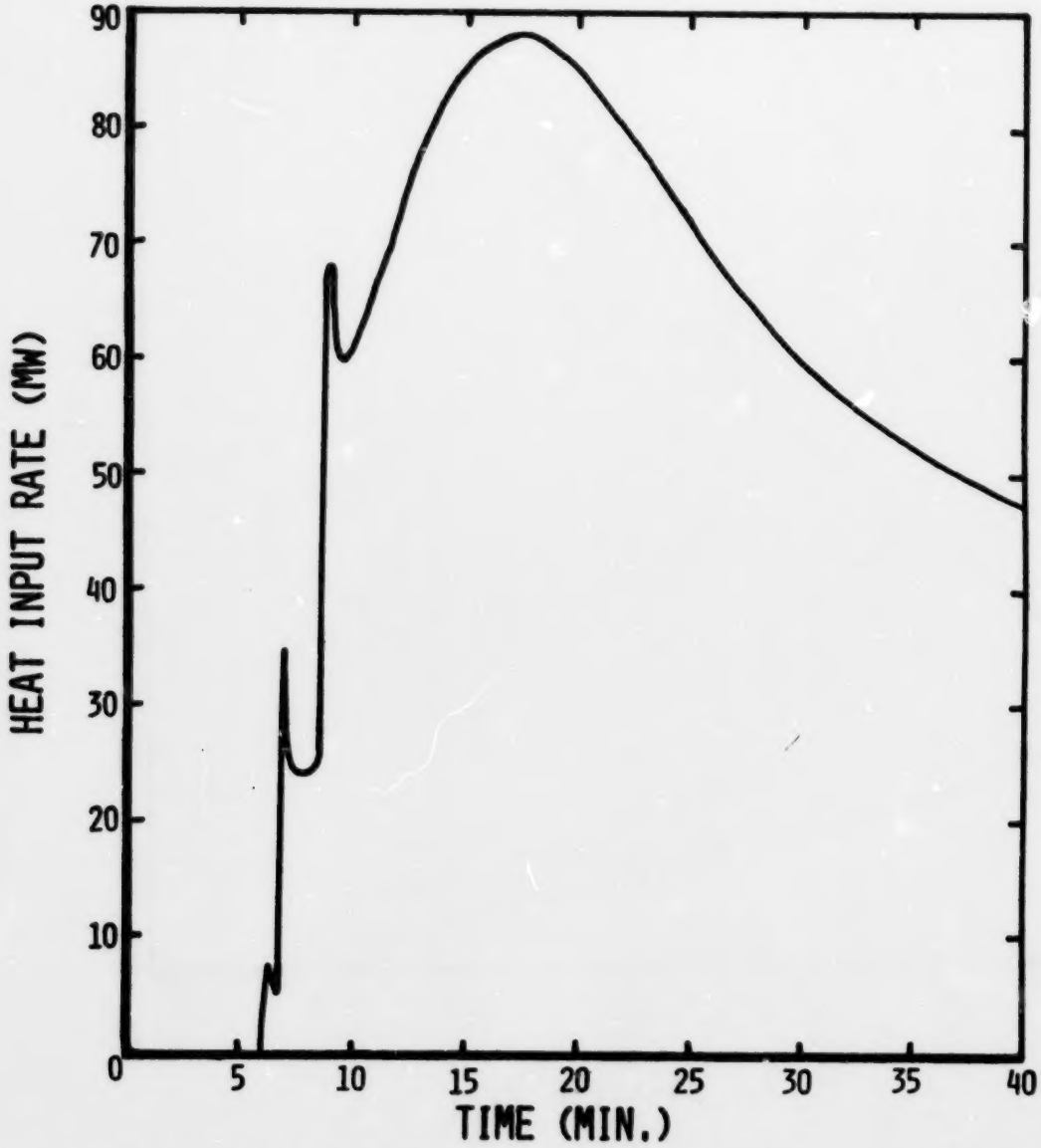


FIG. 3 TOTAL HEAT INPUT RATE TO MODERATOR. BRUCE-A UNIT

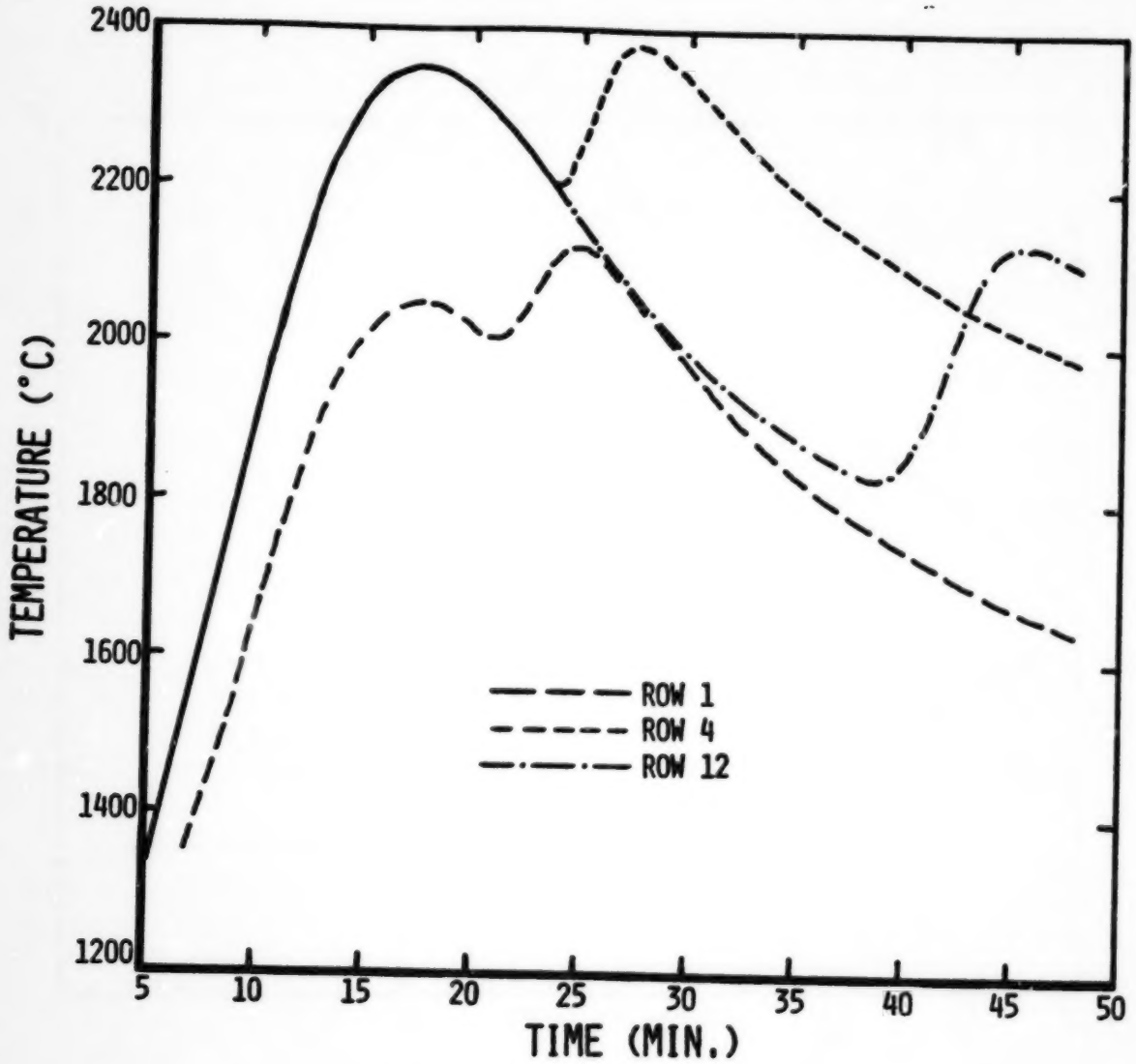


FIG. 4 MAXIMUM FUEL TEMPERATURES IN DIFFERENT ROWS

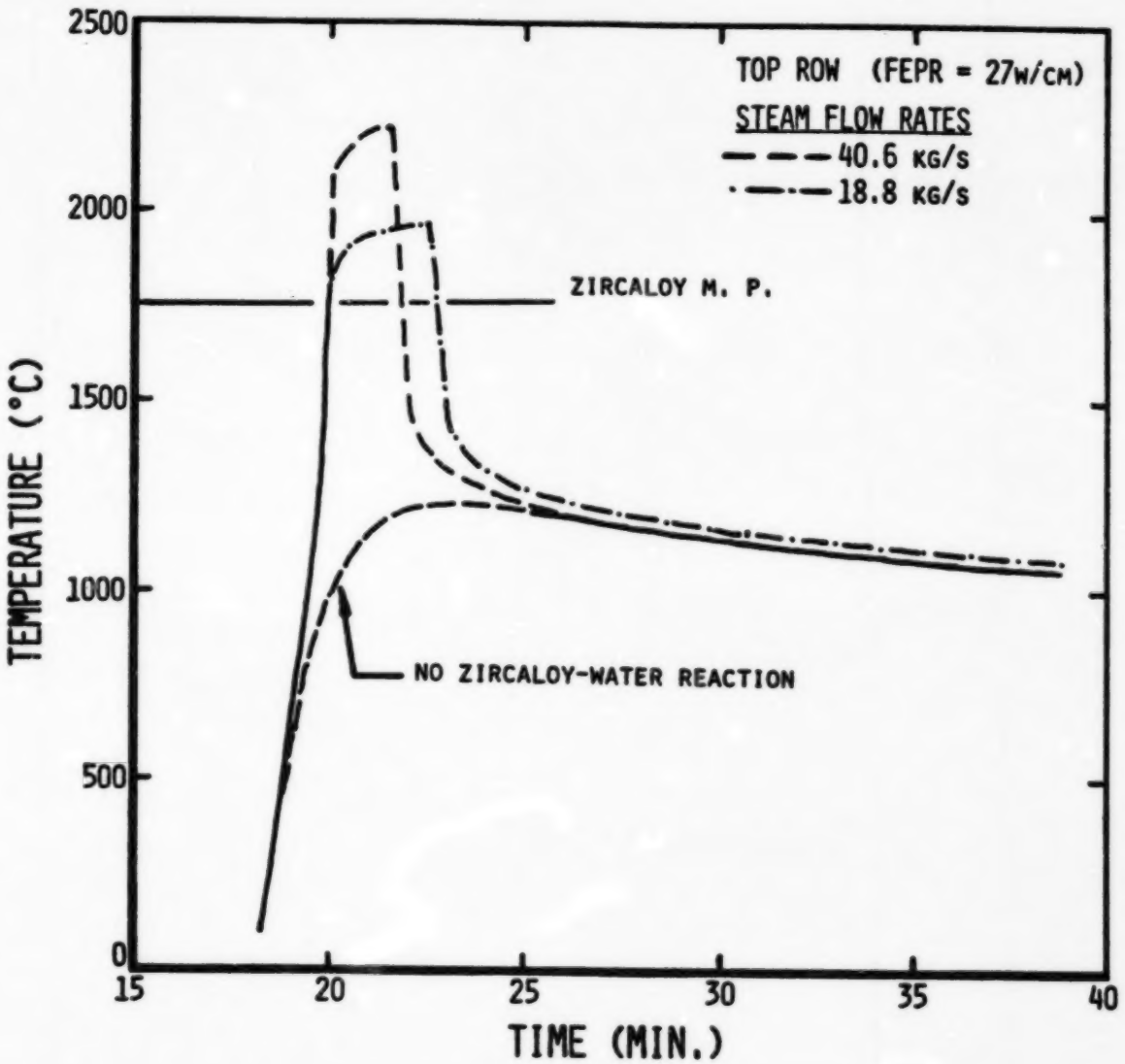


FIG. 5 MAXIMUM CALANDRIA TUBE TEMPERATURES FOR TOP ROW

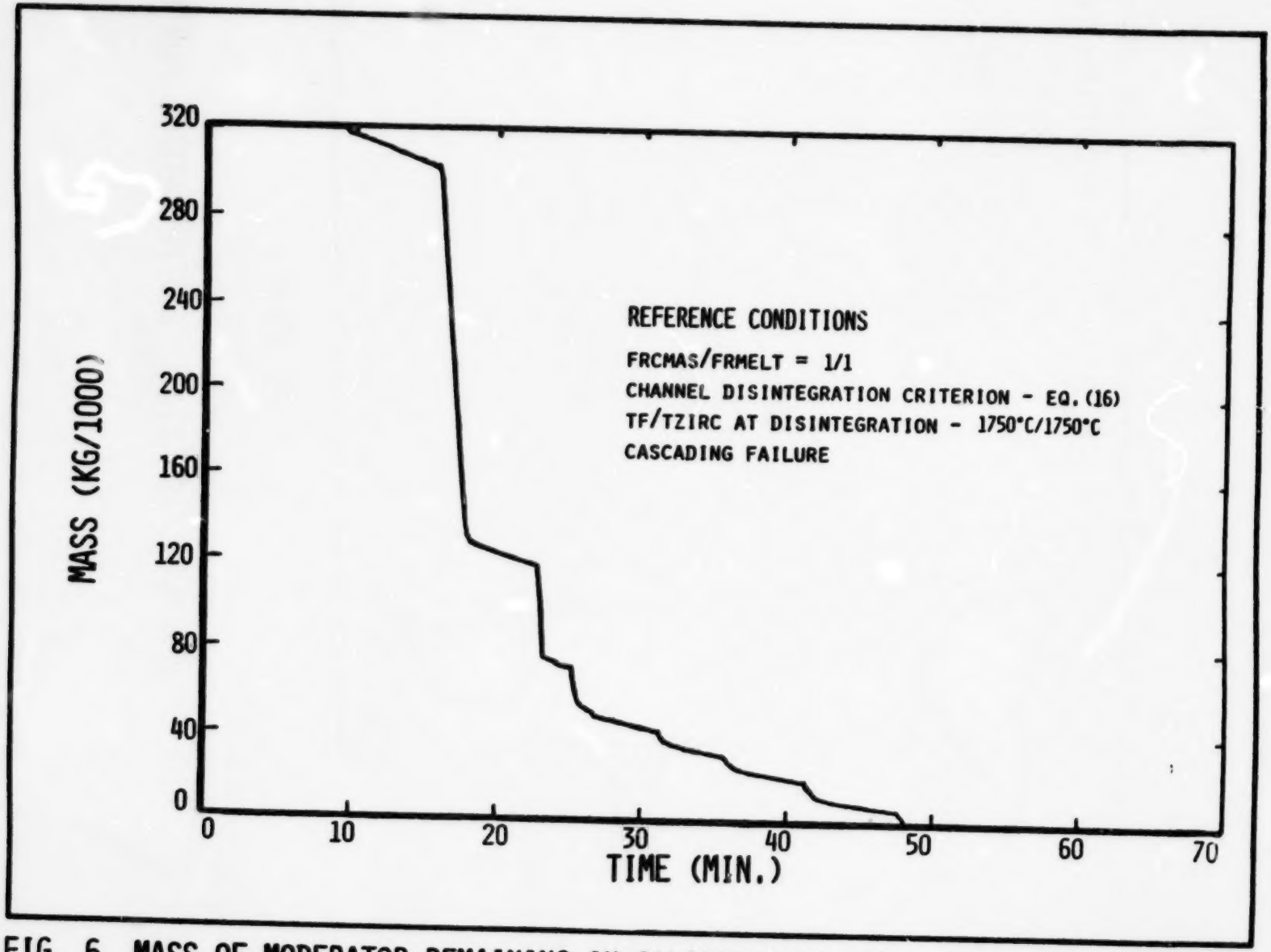


FIG. 6 MASS OF MODERATOR REMAINING IN CALANDRIA VS TIME REFERENCE CONDITIONS

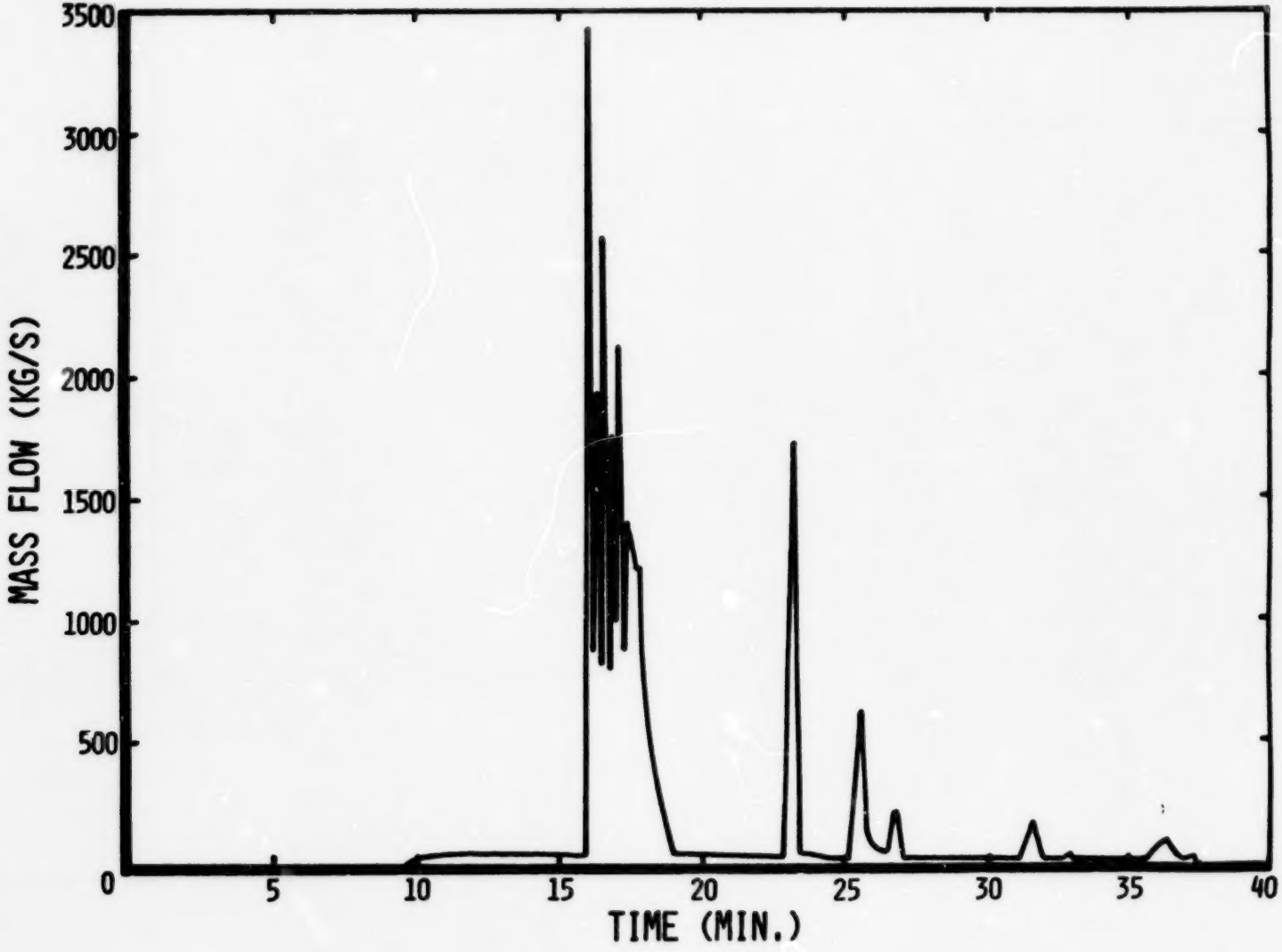


FIG. 7 MODERATOR EXPULSION RATE. REFERENCE CONDITIONS

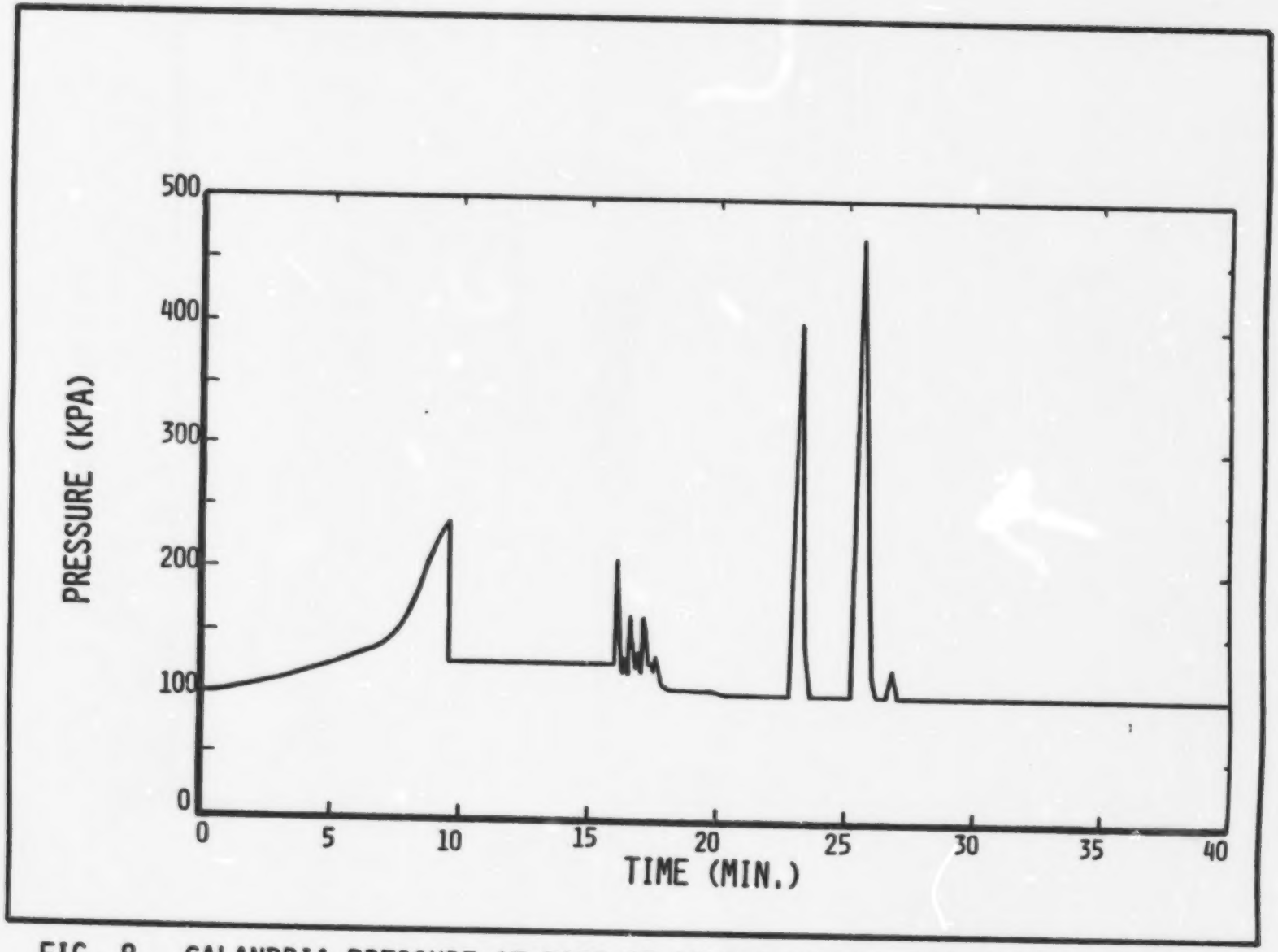


FIG. 8 CALANDRIA PRESSURE AT BASE OF RELIEF DUCTS REFERENCE CONDITIONS

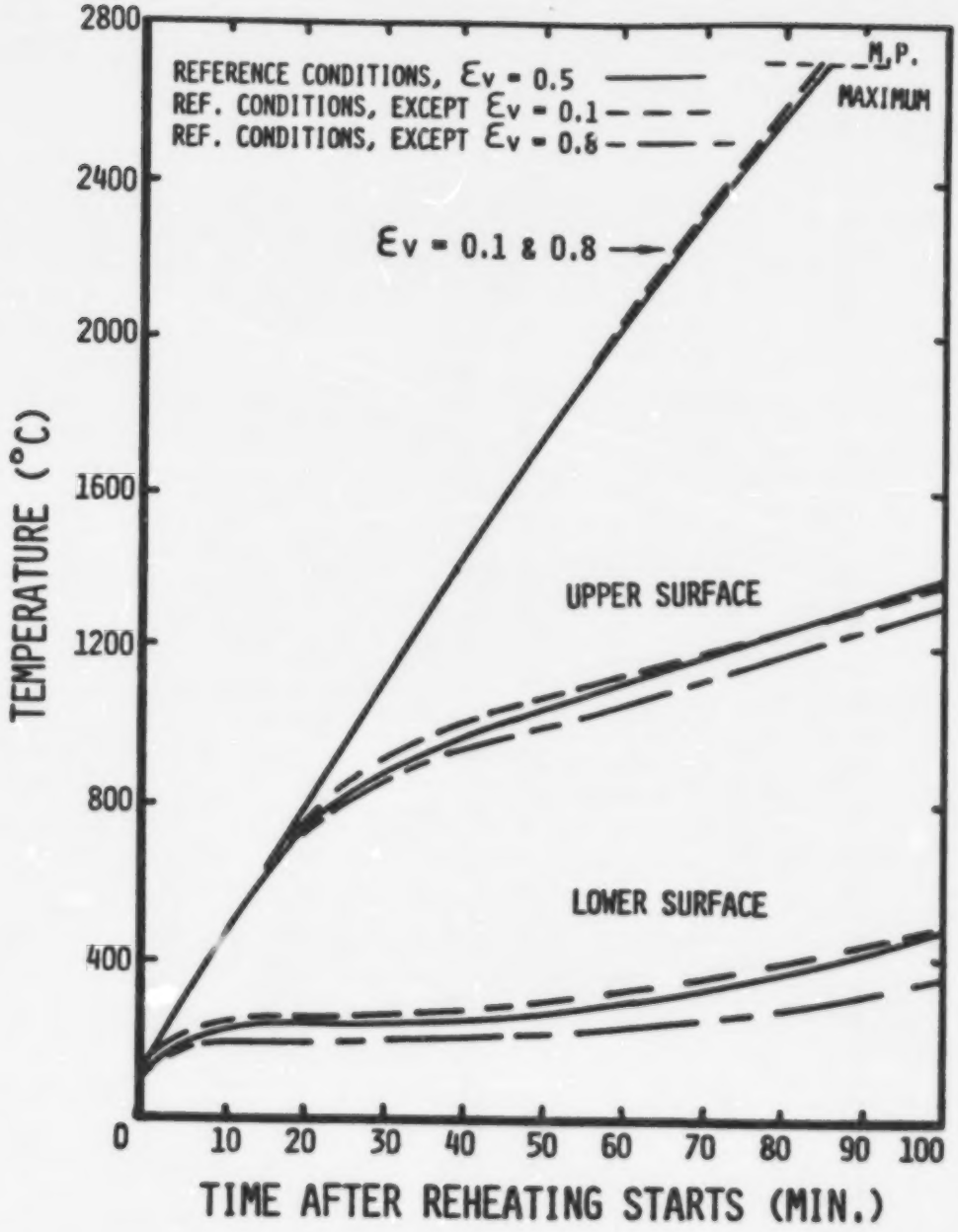


FIG. 9 TEMPERATURES IN POROUS BED OF SOLID CORE DEBRIS

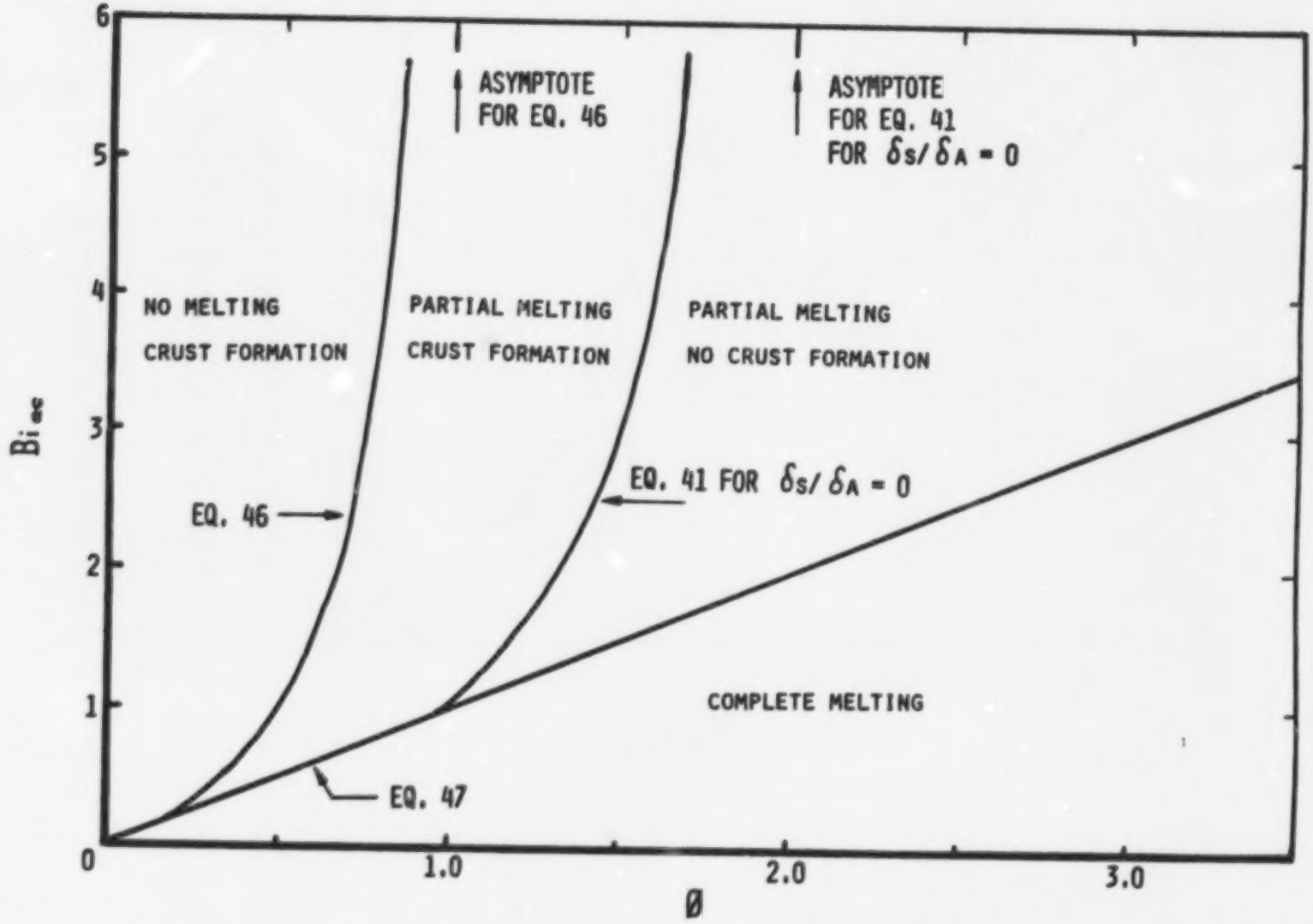


FIG. 10 MAP OF CONDITIONS FOR MELTING OF CALANDRIA WALL

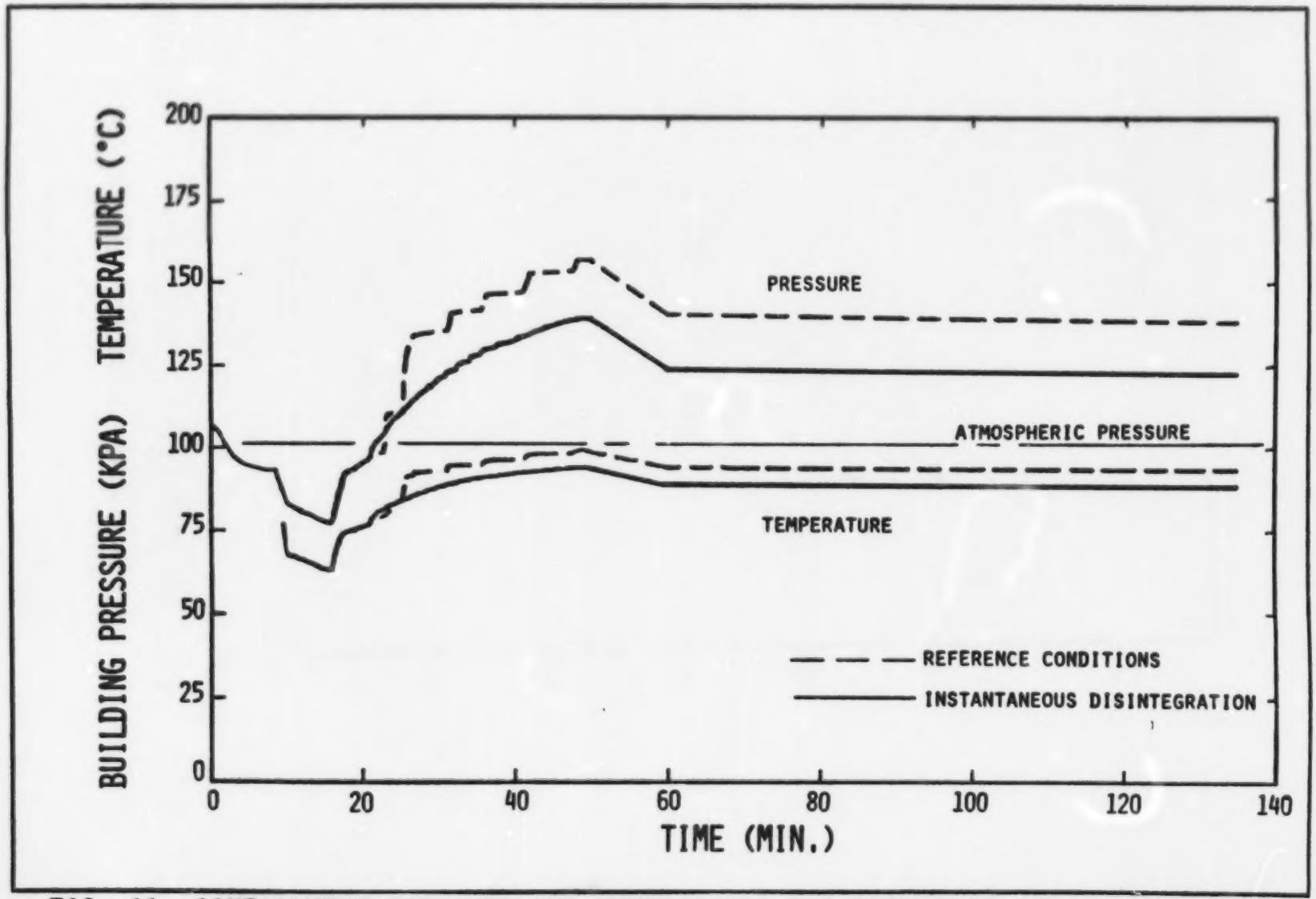


FIG. 11 CONTAINMENT PRESSURE AND TEMPERATURE FOR REFERENCE AND INSTANTANEOUS DISINTEGRATION CONDITIONS.

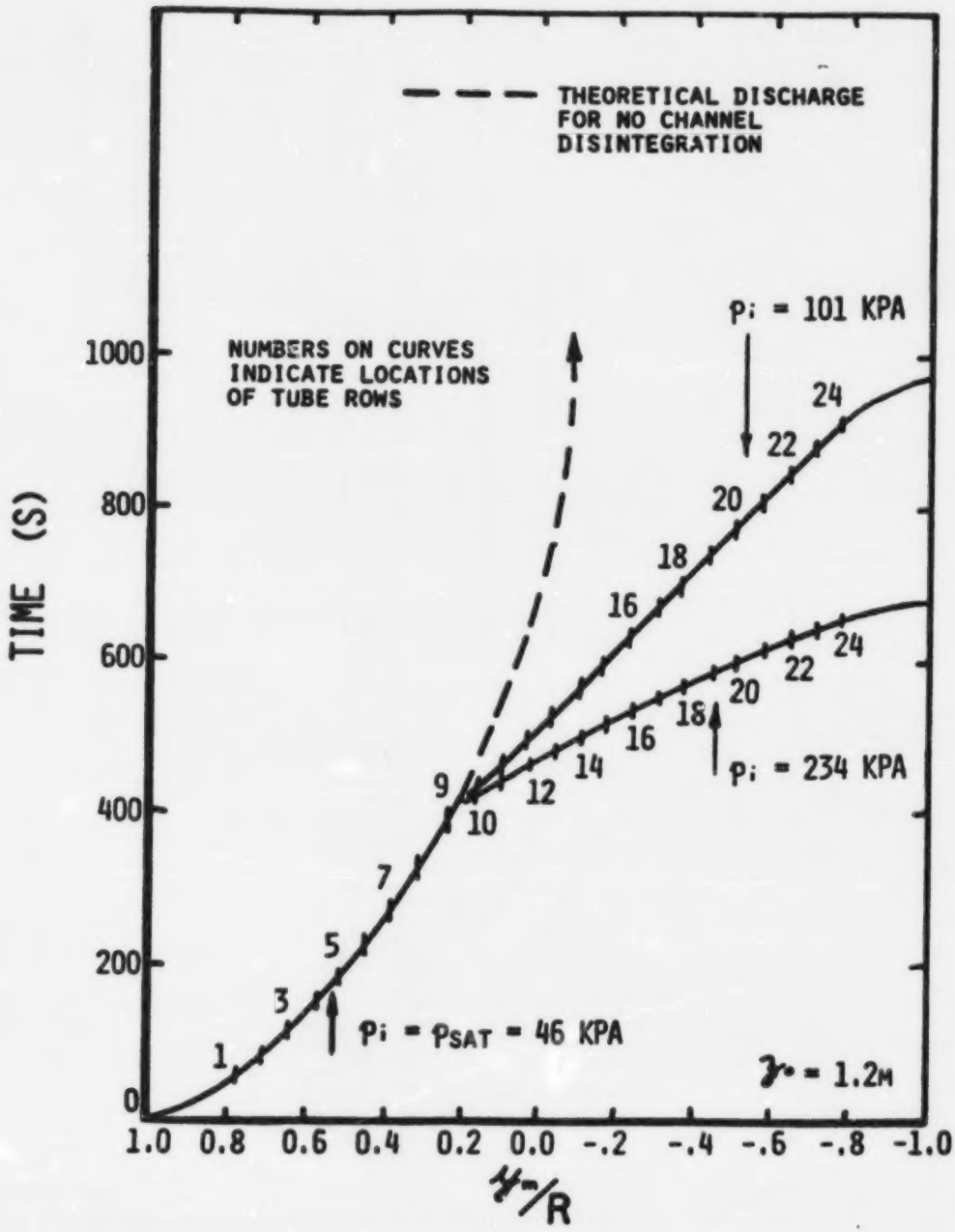


FIG. 12 MODERATOR LIQUID LEVEL IN CALANDRIA. ACCIDENT SEQUENCES S13 AND S14